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An Electro-Optically Controlled Liquid Crystals Diffraction Grating

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Abstract

A new structure for an electro-optically controlled liquid crystal diffraction grating is proposed, which can dramatically simplify the fabrication process of liquid crystal optical gratings. The structure consists of two alternating stripes. Each stripe is a hybrid liquid crystal cell with adjacent stripes oriented perpendicularly. This kind of electro-optically controlled diffraction grating in principle gives 100% diffraction efficiency and no polarization direction dependence. The detailed fabrication process is presented.

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I. Introduction

Large screen projectors with Schlieren optical systems require phase modulating control layers. Usually, these layers are based on mechanically deformable materials like oil films or a mirror on elastomer carriers[1,2]. They modulate the phase by introducing optical path differences to the transmitted(or reflected) light. With a lens, the diffraction orders are focused in one plane where some orders are blocked, the rest being projected onto the screen . If the depth of phase grating varies, the light distribution between the orders changes and so the intensity on the screen varies. Commonly, dark field projection is used where the zeroth order is blocked so that the screen is dark if the control layer is not addressed. The principle of a Schlieren optical system is shown in Fig.1.

Recently, it has been suggested that light-valve projectors using liquid crystal panels as a light modulator are an attractive way to produce large screen images[3,4,5]. However, present methods to fabricate a liquid crystal modulator have the following shortcomings. First, the diffraction efficiency has a strong polarization dependence. This means that at least 50% of incident light is lost when conventional sheet polarizes are used. Second, a high resolution electrode pattern is needed to improve the shape of the modulated phase curve. Without grounding electrodes, the fringe electric field will destroy a square wave phase grating structure and introduce high order harmonic terms which decreases the diffraction efficiency. If grounding electrodes are employed, electrode short will be a serious problem which makes them unpractical for application. One appropriate way to avoid these problems is to directly pattern the liquid crystal aligment layers to generate the LC diffraction grating. Some approaches have been tried. W. M. Gibbons et. al.[6] used an optically controlled alignment polymer to generate the LC

grating structure. More recently, P. J. Bos et. al.[7] developed an optically active diffractive device based on the two-domain TN structure.

In this letter, a new electro-optically controlled diffraction grating using liquid crystals is proposed and its fabrication process is dramatically simplified. This new device in principle has the advantage of 100% diffraction effeciency as well as polarization independence. The detailed fabrication processes and our primary results of cell testing are presented in this letter.

II. The structure of the new LC diffraction grating

The structure of the new electro-optically controlled liquid crystal diffraction grating is illustrated in Fig.2. We have an alternating stripe structure, which is a prerequisite for forming optical diffraction devices. Each stripe is a hybrid liquid crystal cell. The orientation of the liquid crystal in two adjacent hybrid cells are perpendicular to each other. Any incident light can be decomposed into two components, polarized parallel and perpendicular to the stripe lines. These are the optical normal modes of the nematic medium. The alternating two vertical hybrid cells give us a periodic refractive index structure involving n_0 and n_{eff} shown in the figure. n_0 and n_{eff} are the ordinary and effective extraordinary refractive indics of the liquid crystal respectively. This structure acts as a pure phase optical diffraction grating. Moreover, the depth of the modulated phase can be unambiguously controlled by cell voltage.

III. Fabrication Process

According to the structure shown in Fig.2, one plate needs hometropic anchoring. Many techniques can be used to achieve LC homeotropic alignment, For examples, spin coating lecithin,

silane surface treatment and rotational SiOx evaporation surface[8]. We used a silane surfactant. Cleaned ITO coated glass substrates were spin coated with a 0.2% solution of silane(DMOAP) in isopropyl alcohol and water(1:2) in volume. These plates were then baked in a 100°C oven for one hour to allow the chemical reaction to complete.

For the other plate, one photolithography process is needed to pattern the alignment layer such that liquid crystals have perpendicular alignment directions in adjacent stripes. Double rubbing, double SiOx oblique evaporation[9] and double photo-induced alignment techniques[6,10] can be chosen to get this alignment pattern. We used the double rubbing technique[9] because it is convenient for mas production. The polyimide (Nissan PI7311) first was spin coated on a glass substrate then baked around 250° C for two hours. Photolithography is carried out after the first rubbing process. Finally, the substrate is rubbed in the perpendicular direction and the photoresist (Shipley S1400-3) used as a mask is removed by acetone. The test cell of thickness 10μm was filled with E7 from Mark company. The grating resolutions for test cells vary from 200μm to 24μm.

IV. Results and Discussions

As shown in Fig.2, for X and Y compenents, the relative phase difference of light passing through two adjacent stripe is equal to

$$\Delta\delta = \frac{2\pi}{\lambda}\int_0^d (n_{eff}(z) - n_0)dz \qquad (1)$$

$$n_{eff}(z) = n_o n_e / \sqrt{n_e^2 \sin^2(\theta(z)) + n_o^2 \cos^2(\theta(z))}$$

where n_0 and n_e are the ordinary and extraordinary refractive indices of the liquid crystal. $\theta(z)$ is

the angle between the liquid crytal director and the xy plane. The director profile can be adjusted by the cell voltage thus varying $\Delta\delta$. If the relative phase difference is equal to $(2n+1)\pi$, all diffractive spots are going to be at odd order positions which gives us 100% diffraction efficiency. However, if the relative phase difference is equal to $2\pi n$, no diffraction will occur. The n=0 state corresponds to homeotropic alignment which can be approached with a high drive voltage (V~30V). The diffraction efficiency can be precisely controlled by the cell voltage. In order to achive fast drive speeds, it is wise not to increase the cell thickness. Therefore, the phase difference in the diffraction state can be π and the nondiffraction state can be either 2π or zero (homeotropic state). At the no voltage state, under an approximation of $K_1 = K_3$, $\theta(z)$ is linear with z[11] , i.e., $\theta(z)=(\pi/2-\theta_0)z/d$, where K_1 and K_3 are the splay and bend elastic constants of the liquid crystal respectively and θ_o is the liquid crystal pretilt angle at the bottom plate. Combining this relationship with equation (1), we can estimate the suitable cell thickness without missing desired states or introducing additional states.

The experimental setup for studying the electro-optical peoperties of the grating is sketched in Fig.3. The He-Ne laser beam was modulated by an Acoustic Optic Modulator(AOM). The transmitted beam passing through a pinhole is collected by a detector which is connected to a lock-in-amplifier. An AC voltage at 1 kHz was provided by a function generator.

The micoscope pictures of two test cells with stripe width 24μm and 200μm respectively are shown in Fig.4. The nice periodic stuctures indicate good liquid crystal alignment. Fig.5 shows the transmission behavior of zero and first order diffraction of a test cell with a stripe width of 75μm under unpolarized incident laser light. As expected, the m=0 and m=1 orders mirror each other as a function of applied voltage. The transmission peak and valley in the zero order curve

corresponds to a phase difference of 2π(minimum diffraction) and π(maximum diffraction), respectively. Fig.6 illustrates voltage dependent behavior of the first order (m=1) for two input polarizations, one parallel to the stripes, the other perpendicular. This result indicates that the test cell has very good polarization independence of diffraction.

The test cells fabricated gave us nearly perfect diffraction performance. The following factors should be considered to make grating cells have perfect diffraction states. First of all, the perfact diffraction state requires a pure 180^0 phase grating along both x and y direction(see Fig.2). This means the geometry of two perpendicular hybrid cells should be identical. It is hard to get same liquid crystal pretilt angle in both regions because of a photolithography process involved and the vagaries of rubbing. Secondly, disclination lines at the boundary of hybrid liquid crystal stripes reduce the diffraction efficiency. Furthermore, the width of the stripes should be identical and the second rubbing direction should be strictly perpendicular to the first one. We believe the difference in pretilt angle in adjacent stripes is the main impediment to a perfect diffraction state.

V. Conclusion

A proposed new structure for an electro-optically controlled liquid crystal diffraction grating in principle can provide 100% diffraction efficiency and polarization direction independence. The structure consists of two alternative stripes. Each stripe is a hybrid liquid crystal cell; the orientations of the liquid crystal in two adjacent hybrid cells are perpendicular. The test cells confirm the principles. The simple fabrication process makes it compititive for diffractive light valves for large screen projectors. impediments to a perfect diffraction state is also discussed.

Acknowledgments

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Figure Captions

Figure 1. Principle of a Schlieren optical projection system.

Figure 2. New liquid crystal diffraction structure.

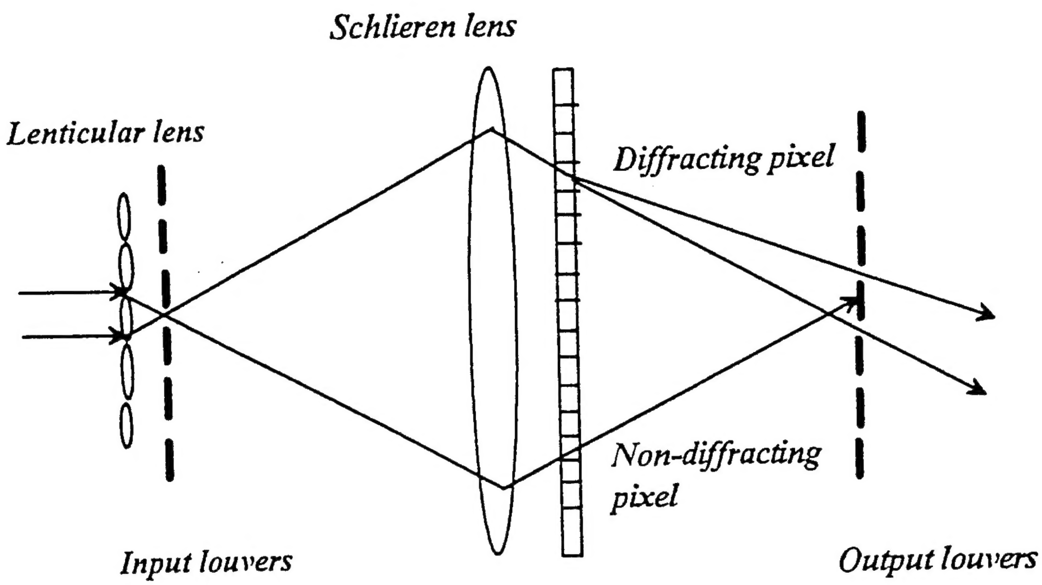
Figure 3. Schematic of set-up used to measure the electro-optical properties of test cells.

Figure 4. Micrographs of two test cells with stripe widths of 200μm and 24μm respectively.

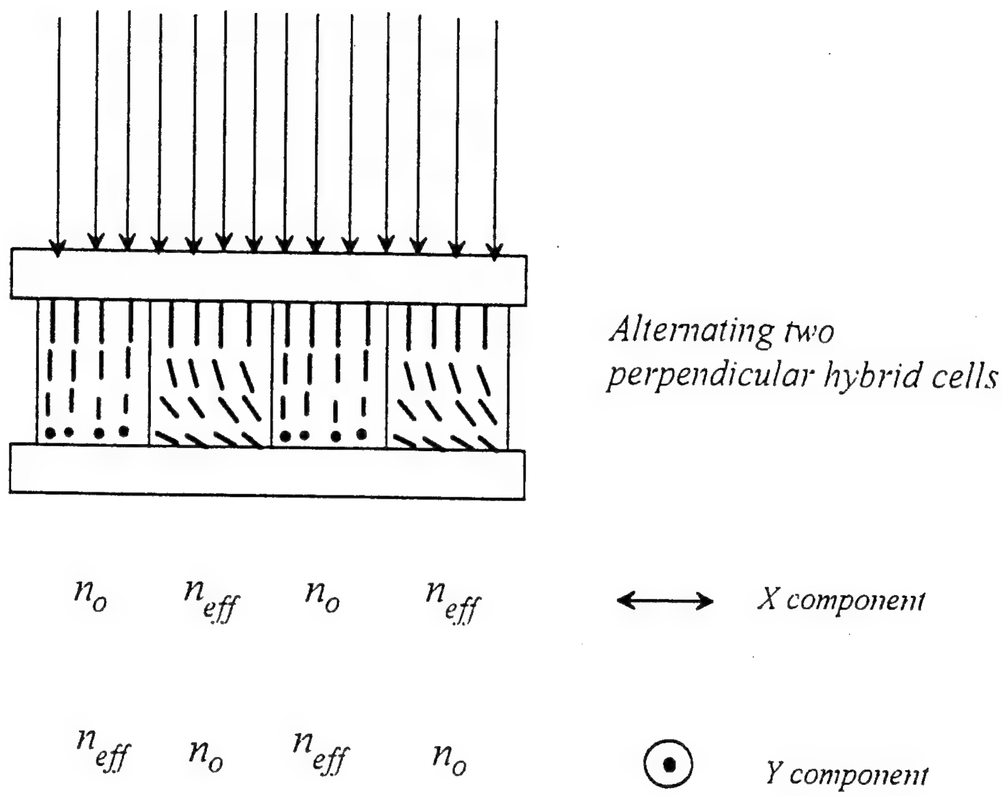
Figure 5. Electro-optical data for zero and first diffraction order.

The test cell stripe width is 75μm and unpolarized laser light is used.

Figure 6. Electro-optical data of first order diffraction for the same test cell as Fig.5 under two input polarization directions, one parallel to stripes and one perpendicular.



Schlieren lens
Lenticular lens
Diffracting pixel
Non-diffracting pixel
Input louvers
Output louvers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perpendicular hybrid cells
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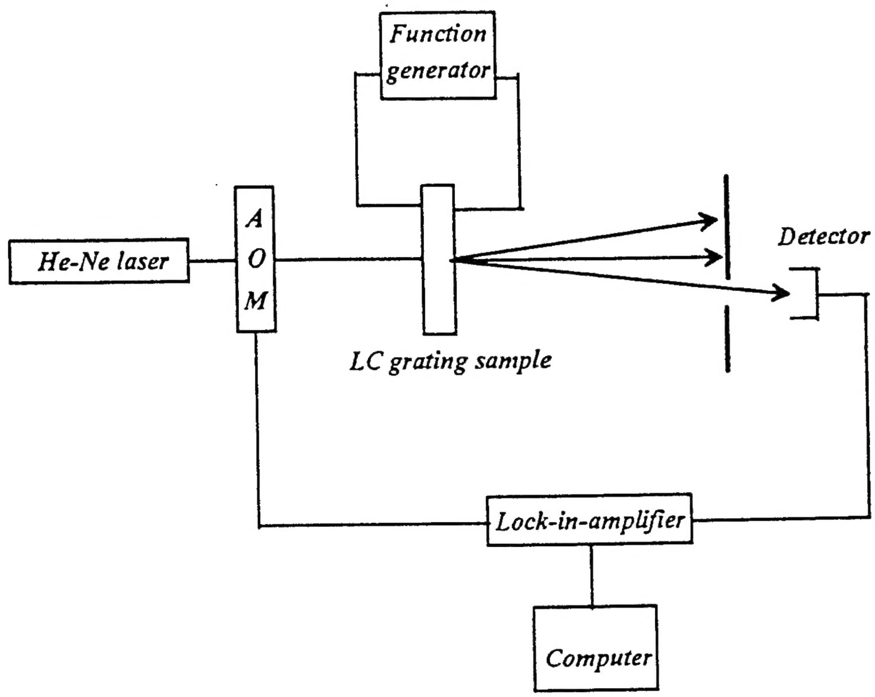
X component
n_{eff} n_o n_{eff} n_o
Y component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A
O
M
LC grating sample
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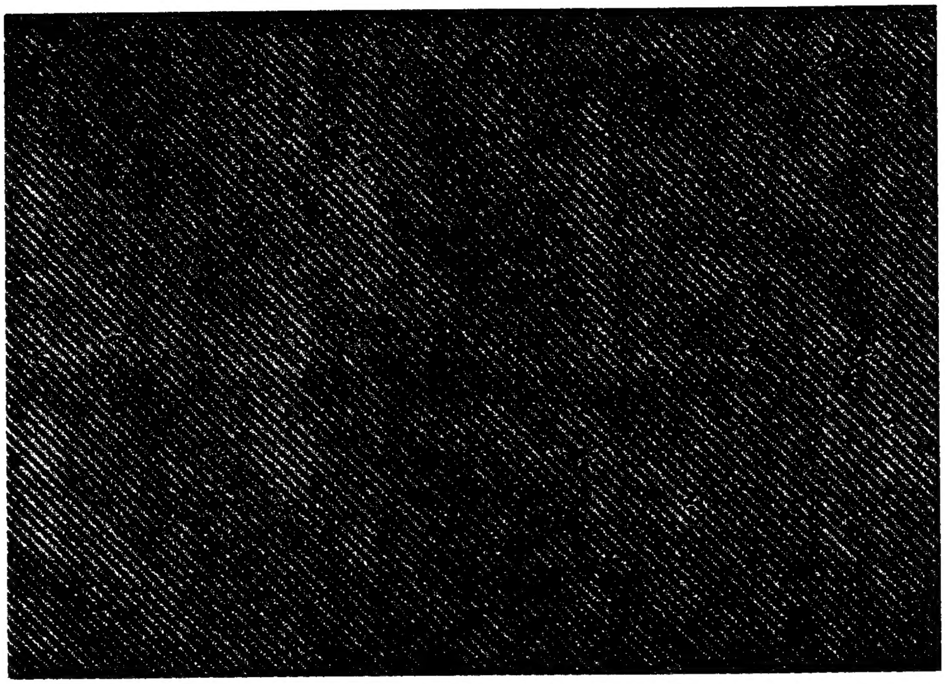
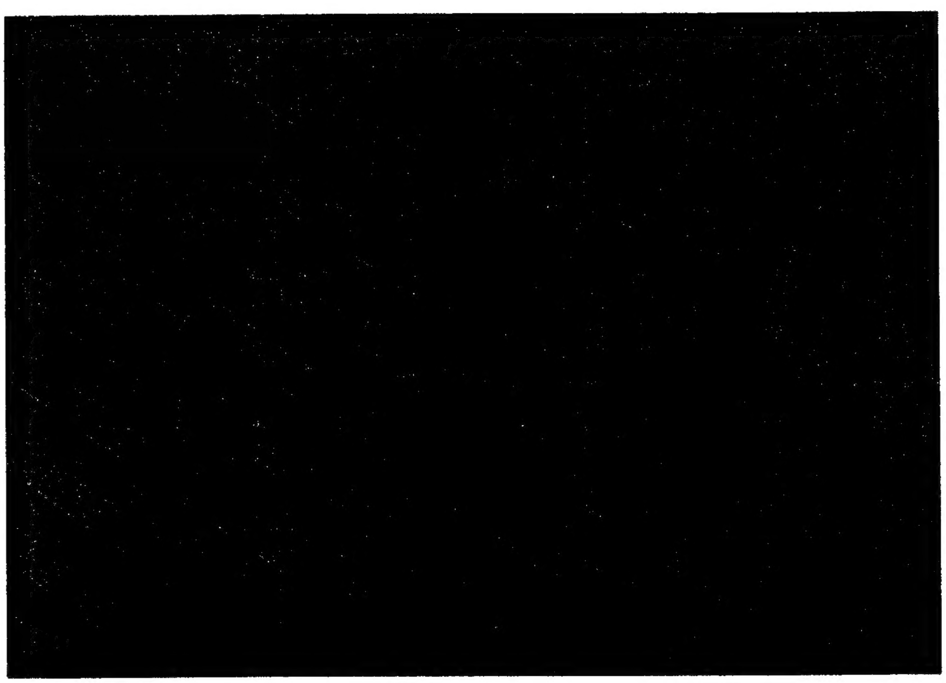
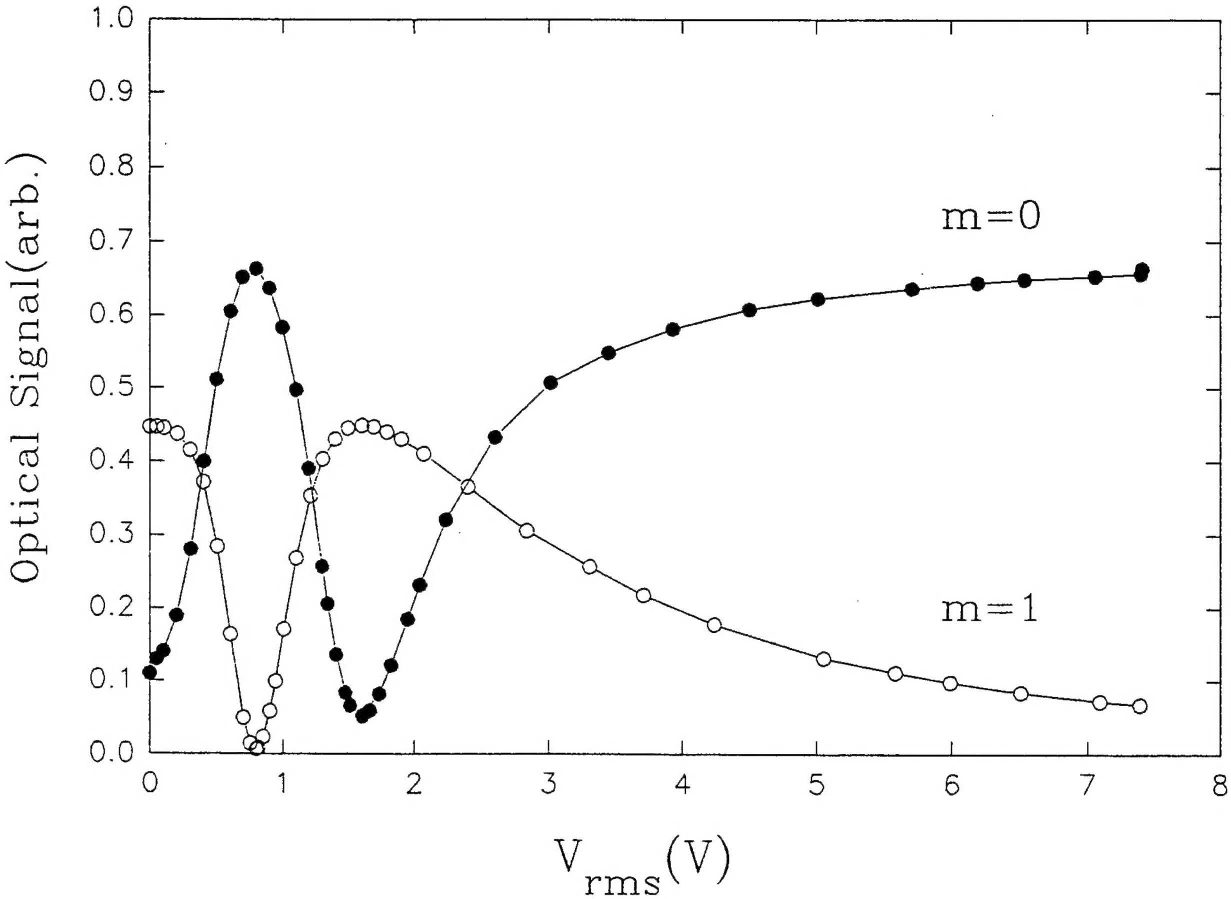
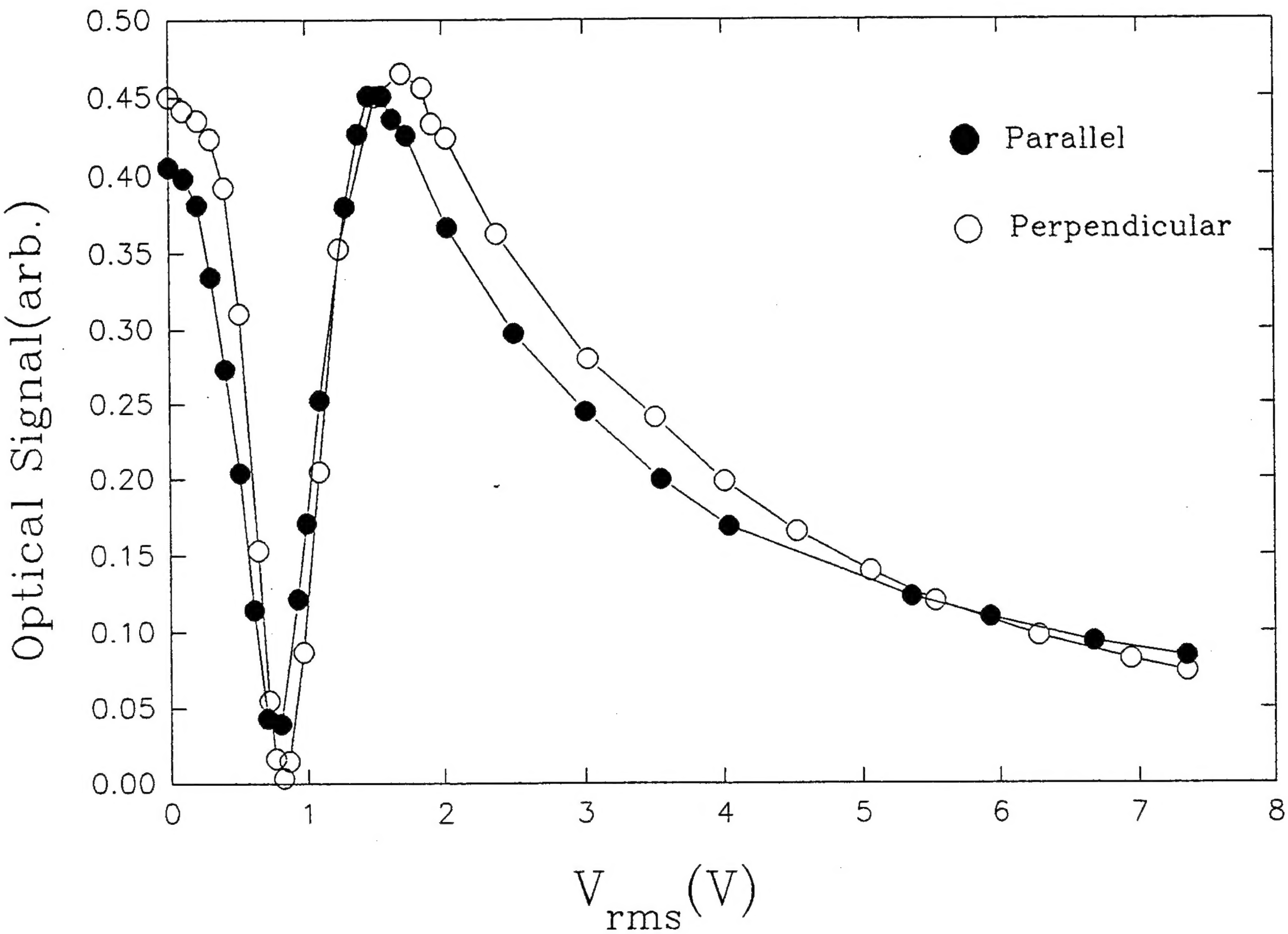






Optical Signal(arb.)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
m=0
m=1
0
1
2
3
4
5
6
7
8
$V_{rms}(V)$



Optical Signal(arb.)
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
1
2
3
4
5
6
7
8
Parallel
Perpendicular
V_{rms}(V)